RESEARCH WITH LARGE AREA IMAGING X-RAY TELESCOPE-SOUNDING ROCKET PROGRAM

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1 Introduction

This report describes the activities of and results from the final year of NASA Grant NSG-5138. The grant had been funded through several cycles of the three year NASA SR&T program. Previous results have been reported in a series of semi-annual and annual reports. We do not repeat what was previously reported. In this final report we report upon only the activities of the past and final year of the grant. Projects begun during the tenure of this grant will continue under the support of a new NASA SR&T grant that was awarded during the most recent three year proposal cycle.

Four lines of study were carried out during the final year. They are:

testing of graded d-spacing multilayer reflectors for hard X-ray telescopes

study of replicated substrates for multilayer reflectors,

design of our system for producing multilayer reflectors,

study of wide field and high throughput X-ray telescopes.

Each of these is described below.

2 Production and Testing of Multilayer Reflectors Upon Replicated Substrates

We entered into a collaboration with O. Citterio of the Brera Observatory to produce replicated substrates from polished masters, coat them with multilayer reflectors, and measure their performance. These coatings consist of many layers of alternating light and heavy materials. This work is the first step in a project to replicate integral cylindrical grazing incidence mirrors from mandrels and coat their interior surfaces with graded d-spacing multilayers. The final product will be a prototype telescope that focuses X-rays up to 100 keV in energy.

Initially, we work with flats rather than cylinders, because they are easier to fabricate and test. Also, the multilayer coatings are initially constant period rather than depth graded period because such coatings are easier to evaluate. They reflect a given energy X-ray at a specific angle, in analogy to Bragg reflection of crystals. Also the replication process is epoxy casting rather than electroforming, the process which we would like to utilize eventually. There is reason to believe that the behavior of both types of replicas will be similar with respect to separating from the mandrel and their ability to provide a smooth substrate for the coatings. Production of small flats is done more conveniently and less expensively by epoxy replication than by electroforming.

In this collaborative project SAO provides the mandrels, the epoxy materials, and is responsible for the application and testing of the multilayer coatings. Since our own facilities that would coat and measure the performance of the replicated substrates were still under development, we subcontracted these two activities to the National Institute of Science Technology (NIST). The Brera Observatory is responsible for producing the replicated substrates.

During the final year of this grant we completed one round of substrate production, coating, and X-ray reflectivity measurements. The results are promising because we obtained good performance from a replicated substrate that was separated with carbon. The process and results are described in a paper by Romaine et al, 1997 which is reproduced in Appendix A.

3 Production and Testing of Graded d-Spacing Multilayer Reflectors Upon Primary Substrates

One of the coatings of great interest is the deep W/Si graded d-spacing multilayer. This coating has a relatively high reflection efficiency up the 69.5 keV K edge of tungsten. We have been collaborating with European Synchrotron Radiation Facility (ESRF), the University of Copenhagen and Osmic, Inc. in producing and testing these coatings. The most significant result of the past year was the publication of a paper by Hoghoj et al, 1997 entitled "Focusing of hard X-rays with a W/Si supermirror" based upon tests carried out at the ESRF. This coating reflects harder X-rays three or more times more efficiently than single metallic coatings. This paper is reproduced in Appendix B.

4 Design of Multilayer Deposition Chamber

With additional support from the Smithsonian Astrophysical Observatory we began the design and development of facilities to deposit multilayer coatings on flat and cylindrical substrates. Our motivation for this is the lack of facilities capable of coating the interior surfaces of cylinders. Therefore, we need our own facilities to proceed with the development of double conical mirrors whose substrates are integral shells. Integral shells are the approach we favor for a future high X-ray focusing telescope system because they offer much better angular resolution than substrates which are segmented into azimuthal quadrants. However, coating the interior surfaces of these closed shells requires special deposition facilities which do not exist at present.

We formulated a plan to develop a facility that contains two chambers, a small much less expensive one that can coat small flats and a large chamber that can coat large cylindrical substrates including the interiors of cylinders. The small chamber which we refer to as the "R&D" chamber can coat flats more quickly and less expensively. It will be used primarily as a research tool, for example, experimenting with novel coating materials. With the larger chamber which we call "the cylindrical chamber" we intend to coat a prototype cylindrical mirror. It will be capable of depositing coatings on the interior surface of a cylinder with diameter between 5 and 12 inches. To obtain useful information for the operation of our future chambers we carried out parametric studies at other facilities of how certain deposition parameters affect the smoothness of the coatings. Hussain et al, 1997 using a deposition facility at Boston University found that the best film qualities, e.g. high density and low roughness at obtained at lower pressure. Although this is not fundamentally new information, some fit is retained as commercial trade secrets and is not in the open literature. Also, the experience of these depositions were useful in the design of own facilities.

5 High Throughput X-Ray Telescopes

An analytic concept study of an ultra high throughput X-ray astronomy was undertaken by the Principal Investigator who does not charge his labor to this program. No equipment was purchased. Therefore, this activity did not result in any expenditure by this program. However, the results were promising and this study will be continued.

APPENDIX A

Application of Multilayer Coatings to Replicated Substrates

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Abstract

We are engaged in a program to develop focussing hard X-ray telescopes in a double conical or Wolter 1 geometry that function up to 100 keV by employing small graze angles and multilayer coatings. Directly polished substrates are not an option because they are too thick to be nested efficiently. The only alternative is to fabricate the very thin substrates by replication. Our objective is the production of integral cylindrical substrates because they should result in better angular resolution than segmented foil geometries. In addition, integral cylinders would be more resistant to possible stress from deep multilayer coatings than segmented ones. Both electroforming of nickel (method of SAX, JET-X, and XMM) and epoxy replication are under consideration. Both processes can utilize the same types of mandrels and separation agents. While electroforming can produce substrates that are thin, the high density of the nickel may result in high weight optics for some missions. For convenience, experimentation with replication and coating is being carried out initially on flats. Our replication studies include trials with gold and carbon separation agents. This paper reports on our efforts with epoxy replicated optics.

Keywords: X-ray Telescopes, Multilayers,Replicated Substrates

1 INTRODUCTION

As part of a program to develop multilayer grazing incidence optics for a hard X-ray telescope, epoxy replication is being investigated for the production of light weight, high resolution cylindrical optics. The

study reported here used epoxy replication of flat substrates (as opposed to cylindrical) to facilitate the coating and X-ray testing of multilayers. Superpolished fused silica substrates were used as masters to produce epoxy replicated surfaces on which multilayers were deposited. This study was undertaken to compare the results of gold and carbon as separation materials in the replication process. After the epoxy replication, nickel/carbon multilayers were deposited and the X-ray reflectivity measured. The multilayers were deposited using dual ion beam assisted deposition at low ambient pressure ($\approx 10^{-4}$ Torr). The results from six samples are reported in this paper; four of the samples were epoxy replicated and the other 2, which were superpolished fused silica were used as controls.

Results of X-ray reflectivity measurements of the multilayers on the 2 different separation materials is reported below and compared with the results from 2 control samples. The carbon replicated substrates show a higher reflectivity at 8 keV than the gold replicas. Results of surface roughness from AFM measurements and from modelled data is also given below; it has been shown [4] that a surface roughness of less than 5 Åis needed for good X-ray reflectivity performance up to 100 keV.

2 SAMPLES

Dual ion beam assisted deposition was used to deposit multilayers on 6 different test samples. Nominal d-spacing and γ (ratio between nickel and period) for the Ni/C multilayers is 40 Åand 0.4, respectively. The 6 samples consisted of: 2 control samples (a bare silica substrate and a silica substrate with 1000 Åof DC magnetron sputtered carbon); 2 epoxy replicated substrates with carbon used as the separation agent; 2 epoxy replicated samples with gold used as the separation agent. Three different coating runs were used to deposit the multilayers. The list of samples coated in each run is shown in table 1. The number of periods deposited was 50 in all cases. During the third deposition run, there was an inadvertent parameter change after the first 28 periods; the last 22 periods of this coating run were deposited with d-spacing of 36 Åand γ of 0.39 (as confirmed by the modelled data). This change results in the 'double Bragg peaks' for these samples which can be seen in the reflectivity data presented below.

3 MEASUREMENTS

3.1 X-ray Reflectivity Measurements

Grazing incidence 8 keV X-ray reflectivity measurements were carried out on all 6 multilayer coated samples and the results are presented in figures 1 through 6. Figure 1 and 2 present the results from the measurements of the multilayers on the 2 control samples which were coated during the same coating run. Figure 1 (S521) is a bare fused silica substrate and figure 2 (S480) is a fused silica substrate with 1000 Åof DC magnetron sputtered carbon. Although the intensity of the first order Bragg peaks is similar for both samples, the intensity of the 2nd and 3rd order peaks of the carbon coated silica has decreased significantly. Table 1 gives the interface roughness calculated from the X-ray model, and as shown, the roughness associated with sample S480 is greater than that of sample S521.

Figure 3 and 4 contain the reflectivity measurements from coating run #2, one carbon replica (S463) and one gold replica (S514). Clearly the Bragg peaks of the gold replica have less intensity than that of the carbon replica; in addition, the carbon replica shows a clear 4th order peak not visible in the measurements of the gold replica. Comparing the carbon replica (fig. 3) with the carbon coated silica (fig. 2), the carbon replica yields the better reflectivity. In the case of both S480 and S463, the multilayer was deposited on a DC magnetron sputtered surface. However, sample S463 was a replica therefore the carbon surface onto which

the multilayer was deposited was the separated carbon, and therefore may have had a smoother surface, as in indicated by the X-ray model results of interface roughness shown in table 1.

The results from the 3rd set of samples coated is shown in figures 5 and 6. Again, one sample (S494) was a carbon replica and one (S492) was a gold replica. As already mentioned, the deposition parameters changed during the run and 2 different d-spacings were deposited, which results in the 'double Bragg peaks' seen in the 8 keV X-ray reflectivity. It is still clear from this data that the multilayers on the carbon replica yield a greater reflectivity than the same multilayers on the gold replica.

3.2 Microroughness Data

It is well known that surface microroughness has a strong effect on the intensity of the grazing incidence specular reflection [2, 3]. This effect becomes more pronounced the higher the energy of incident photons (i.e. the smaller the grazing angle). Microughness results from AFM measurements are presented in Table 1 along with the model calculations of interface roughness for the multilayers.

Surface Microroughness (Å)				
Sample Number	Sample Description	AFM 1μ / 10μ	post-coat (model)	Coating run #
521	bare silica	N/A	4.0	1
480	silica with carbon	N/A	5.5	1
463	carbon replica	2.7/2.3	3.7	2
494	carbon replica	1.1/1.2	3.7	3
492	gold replica	3.4/2.8	5.5	3
514	gold replica	4.6/5.1	5.5	2

Table 1: X-ray modelled and AFM measured microroughness data for the 6 samples discussed in the text

4 DISCUSSION and CONCLUSIONS

The quality of the multilayers deposited on carbon replicas, gold replicas, bare silica and bare silica coated with carbon has been investigated using hard X-rays. The carbon replicas show a higher reflectivity than the gold replicas in both cases and the modelled interface roughness for the carbon replicas is less than that of the gold. The modelled interface roughness of the multilayer on the fused silica with carbon overcoat (sample 480) is also greater than that of the carbon replicas. This may be due to the fact that for the replicas, the multilayer is being deposited on the 'separated carbon' which is the bottom surface of the sputtered carbon, whereas the multilayer deposited on sample 480 is deposited on the top surface of the sputtered carbon.

These preliminary results indicate that using carbon as a separation agent in epoxy replication yields a surface with smaller microroughness, which leads to a multilayer with smaller interface roughness and hence a surface with higher specular reflectivity. This study is ongoing [1] and more complete results will be presented at the conference.

5 ACKNOWLEDGEMENTS

We wish to thank Atkinson Systems of Hudson, NH for providing the DC magnetron carbon coatings. This work was supported by NASA contracts NAG8-1194 and NSG-5138.

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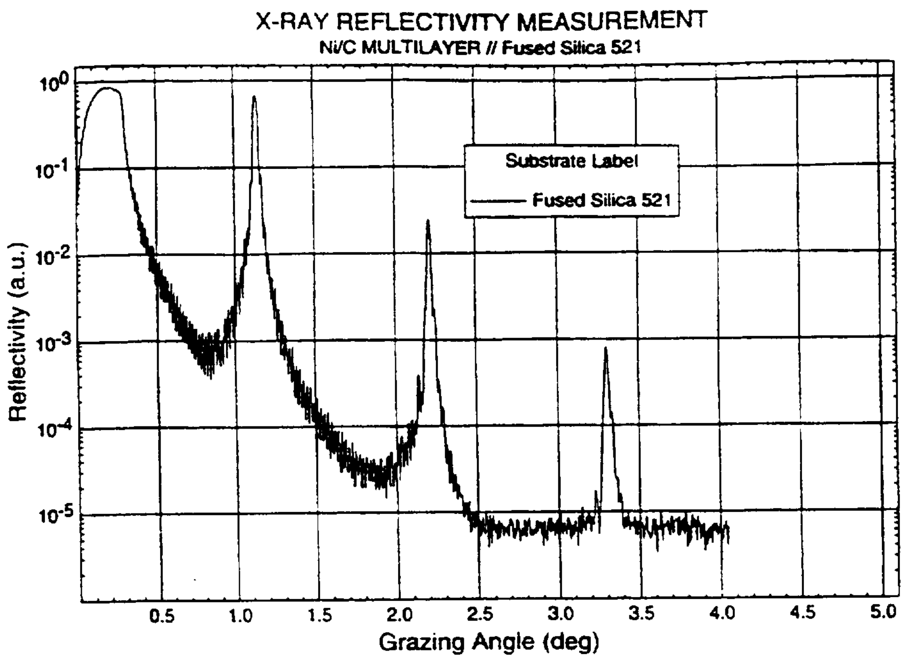


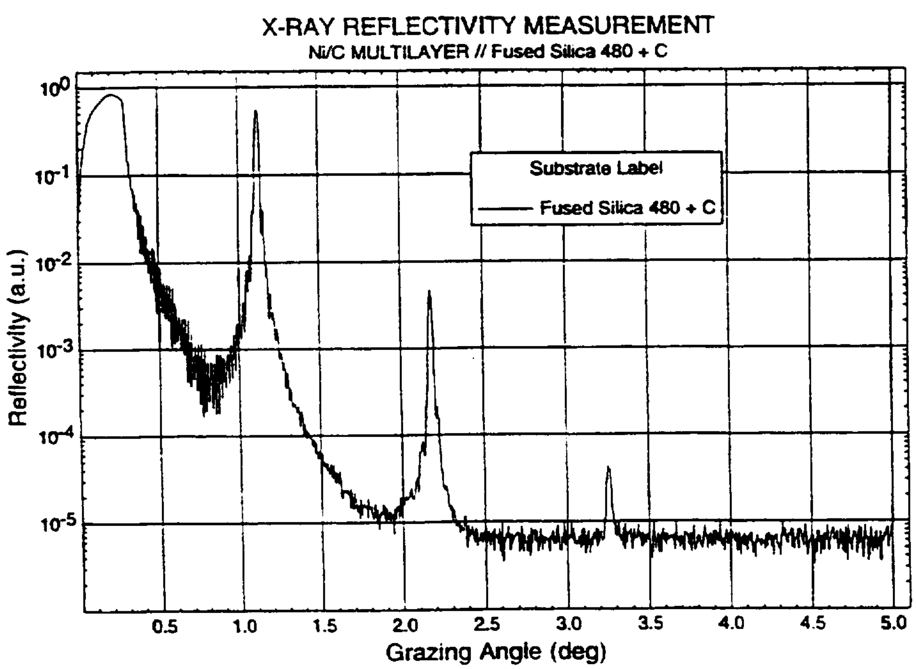
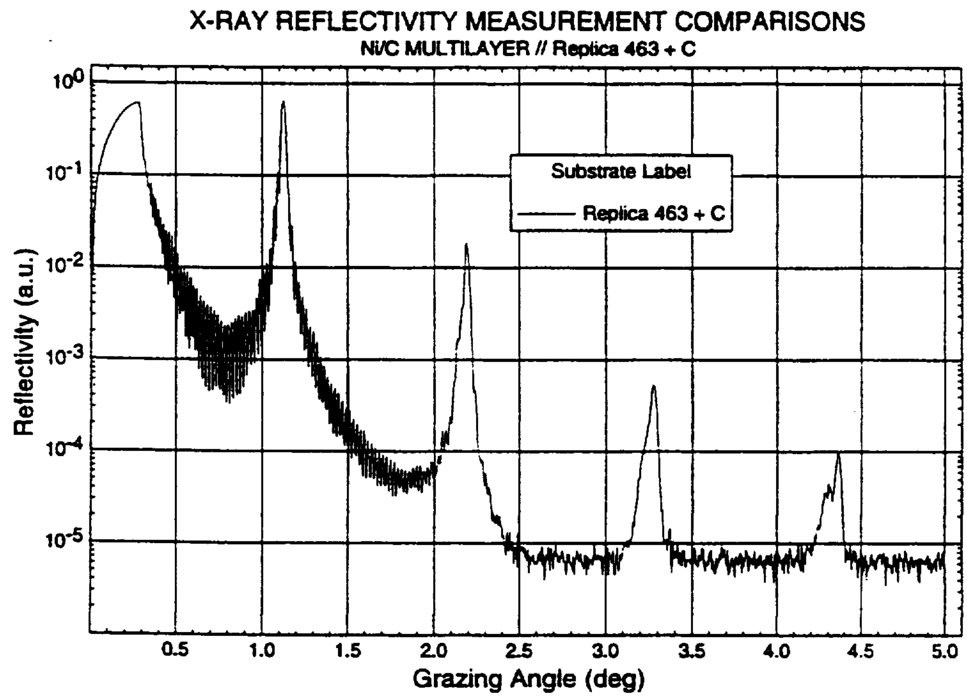


Figure 1. Specular reflectivity vs. grazing angle for multilayers deposited on bare fused silica substrate. (E=8.048 keV)

Figure 2. Specular reflectivity vs. grazing angle for multilayers deposited on fused silica substrate coated with 1000 ÅDC magnetron sputtered carbon. (E=8.048 keV)



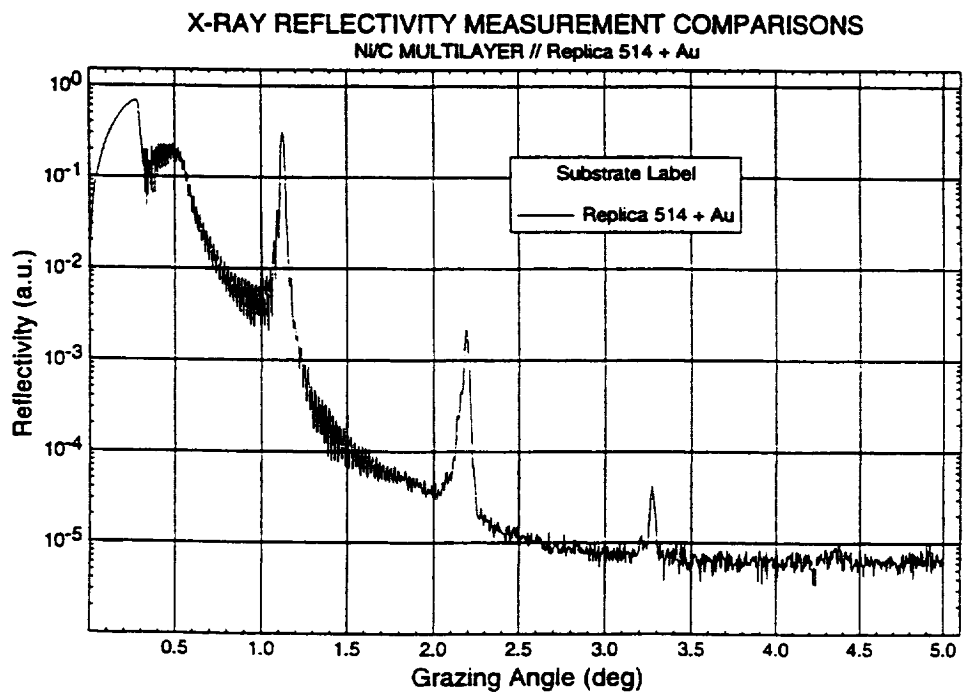
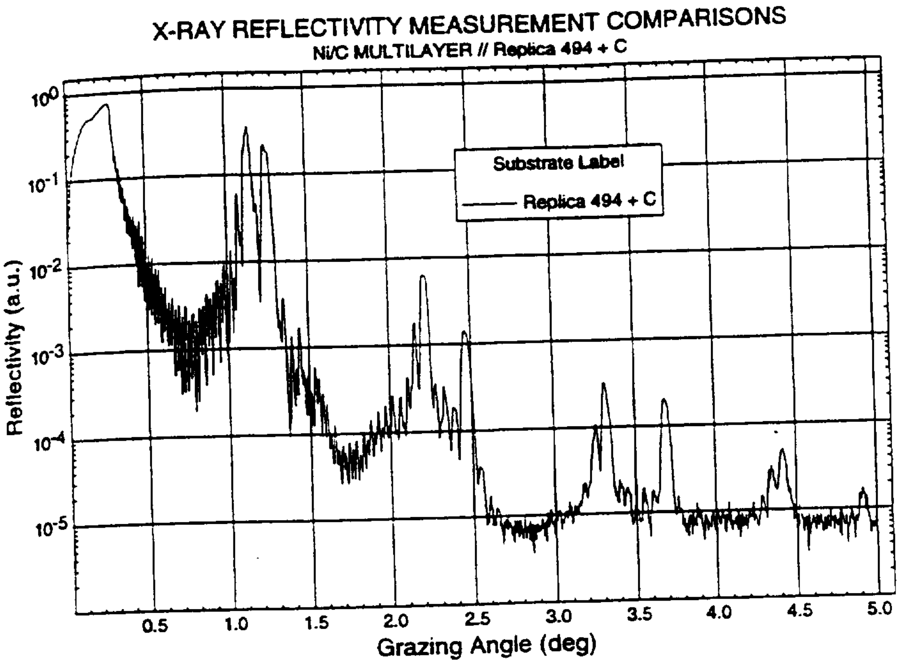


Figure 3. Specular reflectivity vs. grazing angle for multilayers deposited on carbon replica. (E=8.048 keV)

Figure 4. Specular reflectivity vs. grazing angle for multilayers deposited on gold replica. (E=8.048 keV)



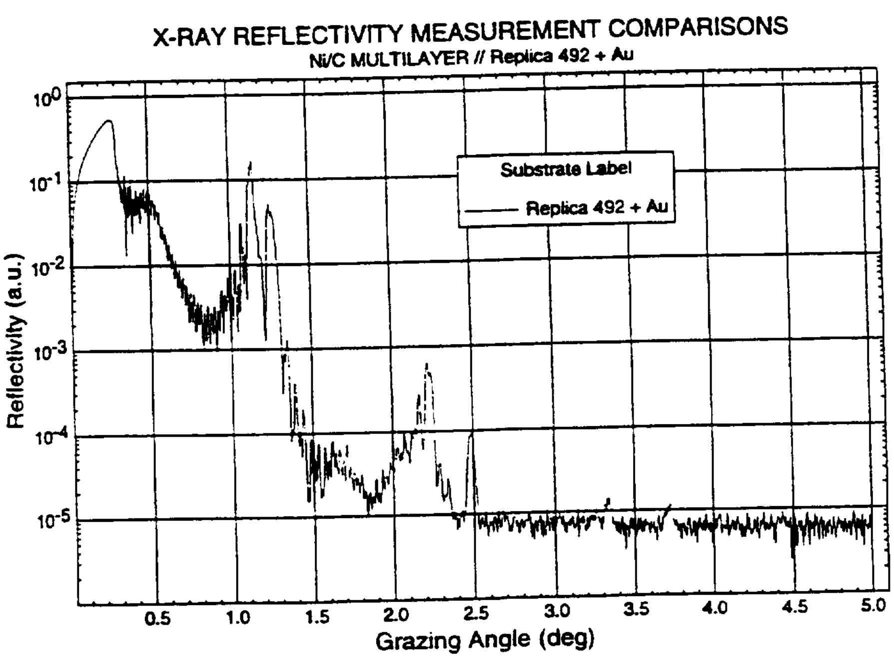


Figure 5. Specular reflectivity vs. grazing angle for multilayers deposited on carbon replica. (E=8.048 keV) (note: 2 different d-spacings were deposited here as discussed in the text.)

Figure 6. Specular reflectivity vs. grazing angle for multilayers deposited on gold replica (see note for figure 5). (E=8.048 keV)

APPENDIX B

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NIM B
Beam Interactions with Materials & Atoms

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Focusing of hard X-rays with a W/Si supermirror

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Focusing of hard X-rays with a W/Si supermirror

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Abstract

The performances of single coating mirrors and supermirrors for hard X-rays are compared. It is found that supermirrors can reflect X-rays at a θ/λ ratio more than three times larger than for single coating mirrors. A W/Si supermirror is applied to the focusing of a white beam of X-rays and is found to efficiently reflect and focus X-rays for energies up to 69.5 keV. At higher energies the performance is limited by the absorption of W above the absorption edge. © 1997 Elsevier Science B.V.

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Keywords: Supermirror; X-ray optics; Hard X-rays; X-ray focusing; W/Si multilayer

1. Introduction

Until recently, the use of reflective optics at short X-ray wavelengths was limited by the low critical angles of mirror materials. These mirrors reflect by total external reflection for grazing angles θ lower than a critical angle θ_c. Above the critical angle, reflection can be obtained by Bragg diffraction in, for example, periodic multilayers [1–3], which have been used to focus [4] X-rays. However, diffraction from periodic structures provides only a limited bandpass and periodic multilayers can therefore not be used where a polychromatic beam is required. For such applications supermirrors [5–9], which are aperiodic multilayers that, like traditional mirrors, show substantial reflectivity for all angles lower than a critical angle, can be used. Supermirrors have for some time been applied to neutron optics [10–12], but they have yet to find their way into X-ray optics and instrumentation. Before that can happen we need to compare the performance of traditional mirrors and supermirrors and to show that supermirrors can be applied to optical problems, such as focusing a divergent, polychromatic beam of hard X-rays.

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Traditional mirrors and supermirrors reflect X-rays by different physical mechanisms, and consequently the limits to their performance as X-ray optical elements are also different. In the following we derive and compare expressions for the maximal scattering vectors q_z that are efficiently reflected by conventional mirrors and supermirrors. The optical index of a mirror material is

$$n = 1 - \delta - i\beta. \quad (1)$$

In the X-ray region the real part decrement δ is typically in the range 10^{-7}–10^{-5}. For small grazing angles where $\sin\theta \approx \theta$ it follows from Snell–Descartes' law that

$$\theta_c \approx \sqrt{2\delta}. \quad (2)$$

In the X-ray region well away from absorption edges, δ can be approximated by the contribution from the Thomson scattering [13]

$$\delta \approx Z(r_0\lambda^2/2\pi)N, \quad (3)$$

where Z is the atomic number, λ the wavelength of the incoming radiation, r_0 the classical electron radius, and N is the number of atoms per unit volume. Eq. (3) allows a fast survey of δ for various elements. The highest value of δ among potential mirror materials is found for iridium. Inserting Eq. (3) in Eq. (2) with the values for Ir, the condition for total reflection ($\theta \leqslant \theta_c$) is

$$\theta/\lambda \leqslant 7.0 \times 10^{-2}\ \mathrm{nm}^{-1} \quad (4)$$

or in terms of θ and energy E

$$E\ [\mathrm{keV}]\ \theta\ [\mathrm{mrad}] \leqslant 86. \quad (5)$$

In a supermirror the reflection mechanism is first order diffraction. The condition for reflection can be found from Bragg's law (neglecting refraction)

$$m\lambda = 2d\sin\theta \quad (6)$$

with the reflection order $m = 1$, and period d. The condition for reflection is then

$$\theta/\lambda \leqslant 1/(2d_{\min}), \quad (7)$$

where $d_{\min}$ is the smallest period in the supermirror. Analogous to Eq. (5) we find

$$E\ [\mathrm{keV}]\ \theta\ [\mathrm{mrad}] \leqslant 6.2 \times 10^2/(d_{\min}\ [\mathrm{nm}]). \quad (8)$$

If desired, Eqs. (4) and (7) can be multiplied by 4π to give a condition for the momentum transfer q_z. It follows that a supermirror with $d_{\min} = 2.4$ nm can show considerable reflectivity at q_z up to three times higher than that of any single layer mirror. However, unlike the neutron case, supermirrors for X-rays have reflectivities much below unity because of absorption [7]. This is particularly true for energies immediately above the absorption edge of one of the layer materials. Interface roughness also reduces the reflectivity, especially for small d-spacings. On the other hand, the increased reflecting angles are an advantage in most optical systems, leading to shorter mirrors less prone to optical aberrations, having a potential for higher resolution and a larger field of view.

2. Experimental setup

The supermirror used in this experiment has been described elsewhere [8]. It is a 600 period W/Si multilayer with the d-spacing of the ith layer from the top being

$$d_i = a(b + i)^{-c}, \quad (9)$$

where $a = 110$ Å, $b = -0.6$, $c = 0.27$, and the ratio of each W layer thickness to the respective bilayer thickness is $\Gamma = d_W/d = 0.33$. The sample was deposited on a $170 \times 50 \times 10\ \mathrm{mm}^3$ superpolished SiC substrate at Osmic Inc. Fig. 1 shows the reflectivity of the W/Si supermirror before bending.

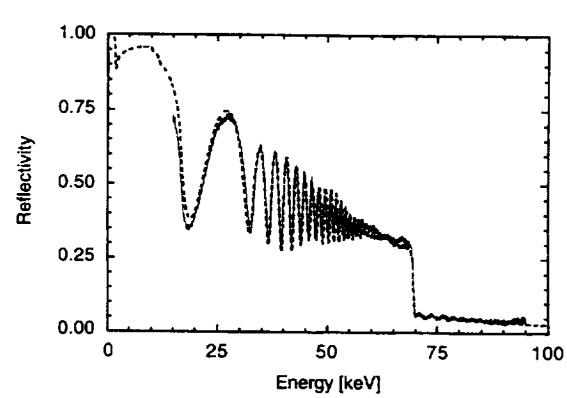

Fig. 1. Measured (solid line) and simulated (dashed line) reflectivity of a flat supermirror at 2.95 mrad.

The supermirror was mounted in a bender [14,15] modified to accommodate thick substrates and bent to a cylindrical shape. The surface figure of the supermirror was verified at every stage of the experiment with a Wyko 6000 Fizeau interferometer [16] capable of measuring height variations down to 0.006 μm over length scales of 0.5–150 mm. Fig. 2 shows the cylindrical figure of the central 40×110 mm^2 of the mirror upon bending. The contour plot in Fig. 2 reveals a small twist and a slightly saddle-like shape. The latter is an effect of antielastic bending [15]. The figure of the bent mirror was further measured with a Long Trace Profiler (LTP) at the Metrology Lab at ESRF [16]. The slope of the surface $\mathscr{S}(x) = \partial z(x)/\partial x$ was measured to a precision better than 1 μrad at 1 mm intervals along the length of the sample. The data are shown in Fig. 3 along with a fit to the data assuming a cylindrical shape. A fit to the middle 80 mm of the mirror used for focusing experiments yielded a radius of curvature $R_c = 630$ m with a RMS slope error $\sigma_{\mathscr{S}} = 1.1$ μrad compared to a cylindrical shape. The height data from the measurements with the Fizeau interferometer can be differentiated in order to obtain slope data and are found to agree well with the LTP data.

The cylindrically bent supermirror was then mounted on a diffractometer in a high energy dispersive setup [17] schematically shown in Fig. 4. The source was a tungsten anode high energy X-ray tube (Philips) operated at 100 kV/1.0 mA giving a Bremsstrahlung spectrum superimposed with the tungsten Kα and Kβ emission. The source size in the focusing plane was defined by a 20 mm thick lead slit S1 with a width of $w_{S1} = 100$ μm placed at the tube exit. The incident beam was further defined by a similar second slit S2 with width 200 μm placed 3.334 m after the first slit. A guard slit was used to remove radiation scattered by S2. The supermirror was placed at a distance $p = 4.000$ m from the first slit. The height of the beam at the mirror was 3 mm.

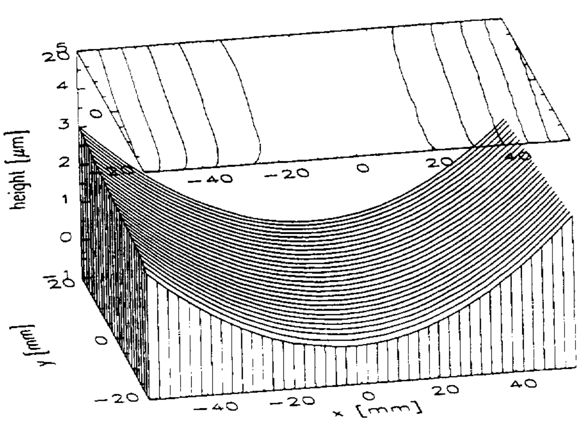

Fig. 2. Figure of the bent supermirror as measured with a WYKO 6000 Fizeau interferometer. The contours are drawn at intervals of 0.5 μm.

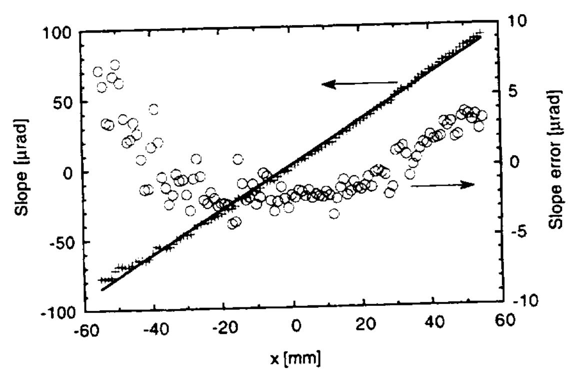

Fig. 3. Slope (crosses) along the x-axis of the bent supermirror as measured with the Long Trace Profiler. The line is a fit to the data assuming a cylindrical shape. The right scale shows the slope error (circles), i.e. the difference between the data and the fit.

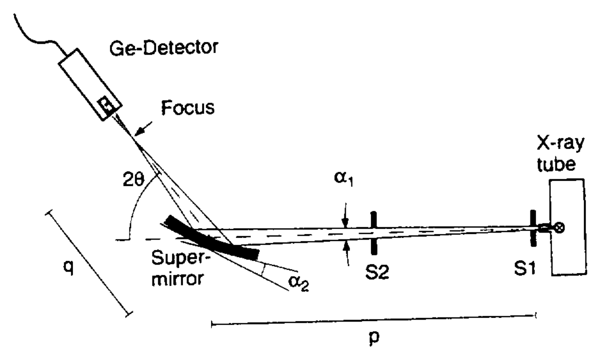

Fig. 4. Schematic (top view) of the setup used in the focusing experiment. S1 and S2 are slits, α_1 is the divergence of the incident beam, and α_2 is the variation of the slope of the mirror over the illuminated area. p is the source to mirror distance and q is the focal length.

The width of the direct and reflected beams were measured using a knife-edge approach. In this approach a polished lead piece mounted on rotation and translation stages with steps of 0.001° and 1 μm, respectively, was scanned through the beam while the intensity was recorded by a Ge solid state detector operated in single channel integral mode. In this method the intensity is seen to drop as the knife edge crosses the beam and the beam profile can be obtained by differentiation. After alignment the supermirror was set to an angle of incidence $\theta = 2.94$ mrad. The beam-spot width was measured at several distances from the supermirror. The smallest width (FWHM) of $F_{meas} = 29.2$ μm was found for a distance $q = 1.000$ m and should be compared to an ideal theoretical width $F_{theo} = (q/p)w_{S1} = 25$ μm. The result is shown in Fig. 5 together with the profile of the direct beam measured at $q = 1.000$ m. The direct beam profile has a trapezoidal shape as expected from a beam defined by slits. The FWHM for the direct beam was $D_{meas} = 295$ μm, the integrated intensity was 5604 c/s with a peak flux of 20 c/s/μm, while for the focused beam the integrated intensity was 2401 c/s with a peak flux of 77.3 c/s/μm. The results obtained with knife-edge scans were verified by taking photos of the direct and reflected beams using Kodak HR X-ray film. The results are shown in Fig. 6.

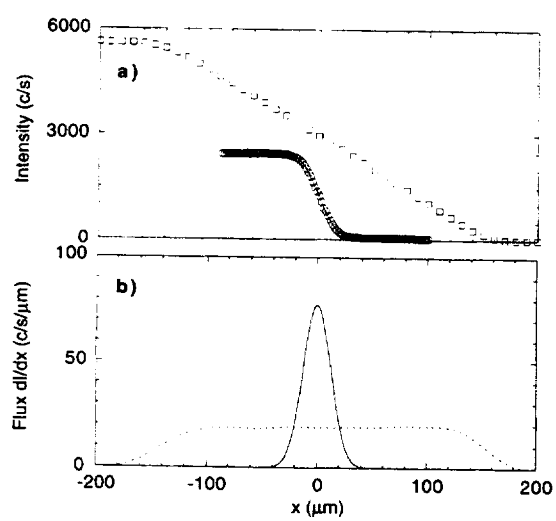

Fig. 5. (a) Intensity as a function of knife-edge position for the direct beam as defined by slits (squares) and the focused beam (circles) for $\theta = 2.94$ mrad at $q = 1000$ mm. A fit to the data assuming a Gaussian flux distribution for the focused beam is shown (solid line); (b) beam flux profile in the direction of the scan for the direct beam (dashed line) and focused beam (solid line) as found from differentiating the intensity with respect to the knife-edge position.

From geometrical optics the distance mirror to focus q is given by the lens equation

$$\frac{1}{q} + \frac{1}{p} = \frac{2}{R_c \sin\theta} \tag{10}$$

but the experimentally observed q was 17% smaller than the one obtained from Eq. (10). However, using the raytracing program SHADOW [18] we find the value of q to be strongly dependent on the deviation of the surface figure from the cylindrical case. Furthermore, the measured values for the width of the focused beam was found to be in good agreement with values obtained from raytracing using the actual shape of the mirror as measured with the LTP.

Fig. 7 shows the reflectivity $R(E)$ of the bent supermirror at $\theta = 2.94$ mrad. The reflectivity was found by measuring the spectrum of the reflected beam with the Ge-detector connected to a multichannel analyzer and normalizing it with

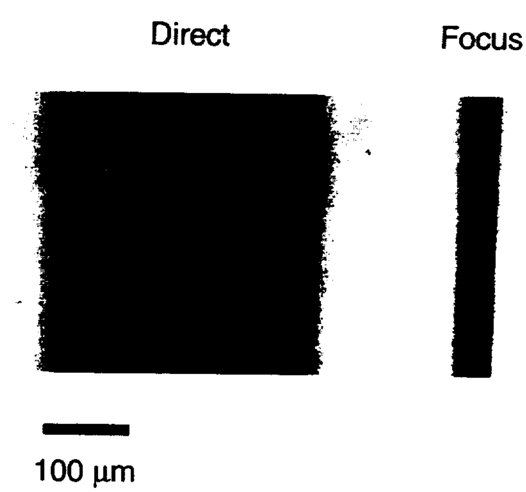

Fig. 6. Photos of the direct beam (left) and focused beam (right) at $q = 1000$ mm. The photos were recorded on Kodak HR X-ray film and magnified using an optical microscope.

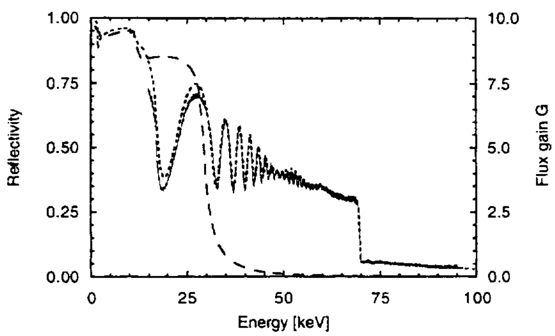

Fig. 7. Measured (solid line) and calculated reflectivity (short dashed line) as a function of energy at an angle of incidence $\theta = 2.94$ mrad for the bent W/Si supermirror. The flux gain in the focal plane as compared to the direct beam is given on the right ordinate. Compared with Fig. 1 only small differences in the reflectivity modulation are observed. The differences are due to the increased range of incidence angles. The gain in flux is a result of the focusing of the beam as shown in Figs. 5 and 6. For comparison the theoretical reflectivity of an Ir mirror is shown (long dashed line).

the spectrum of the direct beam. The measured reflectivity is higher than 30% for energies lower than the W absorption edge at 69.5 keV. For energies below 20 keV it was difficult to obtain absolute reflectivities due to the behavior of the detector response function combined with low intensity. The reflectivity simulations shown in Fig. 7 were done using the recursive method of Parratt [19] and the design parameters. The drop in reflectivity with energy is very sensitive to the roughness, which was fitted to be $\sigma = 4.3$ Å using the expression proposed by Névot–Croce [20]. The slits defined the divergence of the incident beam to $\alpha_1 = 0.06$ mrad. As seen in Fig. 3 the slope varied by $\alpha_2 = 0.14$ mrad over the 80 mm illuminated part of the mirror. From Fig. 4 it is seen that α_1 and α_2 contribute to the angle of incidence θ with opposite sign. Furthermore, the intensity distributions are both well approximated by the uniform distributions as seen from the intensity profiles of the direct beam in Fig. 5 and the distribution of slope in Fig. 3. Consequently, the simulated data were convoluted with a uniform distribution of width $\alpha = \alpha_2 - \alpha_1 = 0.08$ mrad and with the Gaussian energy resolution σ_E of the Ge detector using Eq. (11).

$$R(E,\theta) = \frac{1}{\sigma_E\sqrt{2\pi}\alpha} \int_{E-4\sigma_E}^{E+4\sigma_E} \int_{\theta-\alpha/2}^{\theta+\alpha/2} R(E',\theta') \times \exp(-((E-E')/\sigma_E)^2/2)\,\mathrm{d}\theta'\mathrm{d}E'. \quad (11)$$

From monochromatic experiments σ_E was found to change from about 0.12 keV at $E = 15$ to 0.18 keV at $E = 100$ keV.

The reduction of the beam size gives a gain in flux while the reflectivity lower than unity gives a loss. When comparing focusing optics to simply reducing the size of the direct beam with slits, the interesting value is the flux gain G, which can be defined as

$$G(E) = (D_{\mathrm{meas}}/F_{\mathrm{meas}})R(E), \quad (12)$$

where D_{meas} and F_{meas} are the measured widths of the direct beam and focused beam, respectively. $G(E)$ is plotted on the right y-axis of Fig. 7. The flux gain is in the range 7–3 in the 20–70 keV energy range.

3. Conclusion

A comparison of supermirrors to conventional mirrors shows that supermirrors have the ability to efficiently reflect X-rays at q_z up to more than three times the critical angle or energy of conventional mirrors. Such performance makes supermirrors interesting optical elements for high energy X-rays.

The results demonstrate the capability of bent supermirrors to focus X-rays at high energies. At $\theta = 2.94$ mrad the bent W/Si supermirror showed reflectivities of 30–70% for energies below the tungsten absorption edge at 69.5 keV. By bending the supermirror to a near cylindrical shape and applying it in a 4 to 1 focusing scheme in one dimension the beam was focused to a size 10 times smaller than that of the direct beam. The resulting flux gain was from 3 to 7 in the above mentioned energy range. By using other multilayer materials similar results should be possible even for energies above 100 keV. The focusing properties of the bent supermirror are well understood and no deterioration of the reflectivity was observed upon bending.

The fact that line to line focusing should be done with an elliptical mirror rather than a cylindrical one has little influence on the results. However, in the case of a synchrotron beamline with smaller source size and larger source demagnification q/p the contribution of spherical aberrations to the focal width would be more significant and an elliptical mirror should be used (as shown in [15]). By focusing in two dimensions even larger gains in flux could be obtained. Finally, this first experiment with a focusing supermirror shows the potential of supermirrors as X-ray optical elements and the new possibilities they open in X-ray instrumentation in areas such as synchrotron radiation and astrophysics applications.

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